Fiber optics for passive seismic monitoring:

earthquake observations and ambient seismic noise interferometry

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Collaborators:

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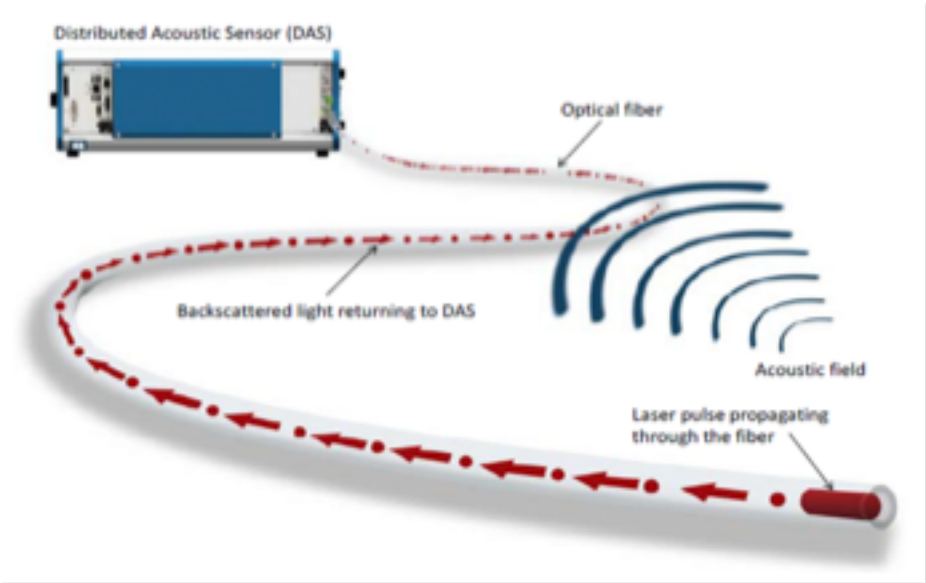
Shan Dou (LBL)
Steve Cole (OptaSense)

Outline

- **What is distributed acoustic sensing?**
- We record earthquake arrivals, but different waveforms
- We can get ambient noise interferometry signals from throughout fiber arrays
- Conclusions and challenges going forwards

Distributed acoustic sensing (DAS)



Change in backscattered light gives information about :

- temperature, DTS
- static/slow strain, DSS
- **dynamic axial strain rate, DAS**

F. Tanimola, D. Hill, 2009, Journal of Natural Gas Science and Engineering.
T.M. Daley, et al., 2013, TLE.

Strain is a tensor quantity

longitudinal waves

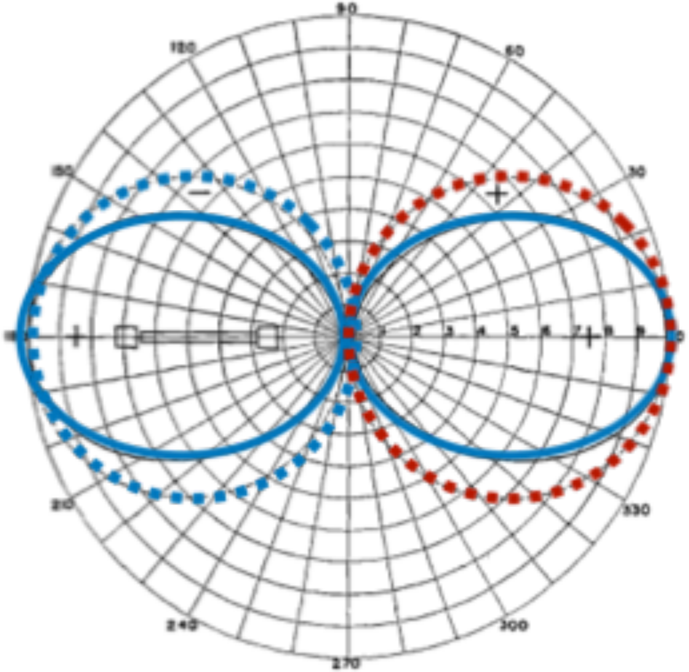


Fig. 7. Directional response characteristic of linear strain seismometer for longitudinal apparent waves. Pendulum directional response characteristic is shown in dotted lines.

transverse waves

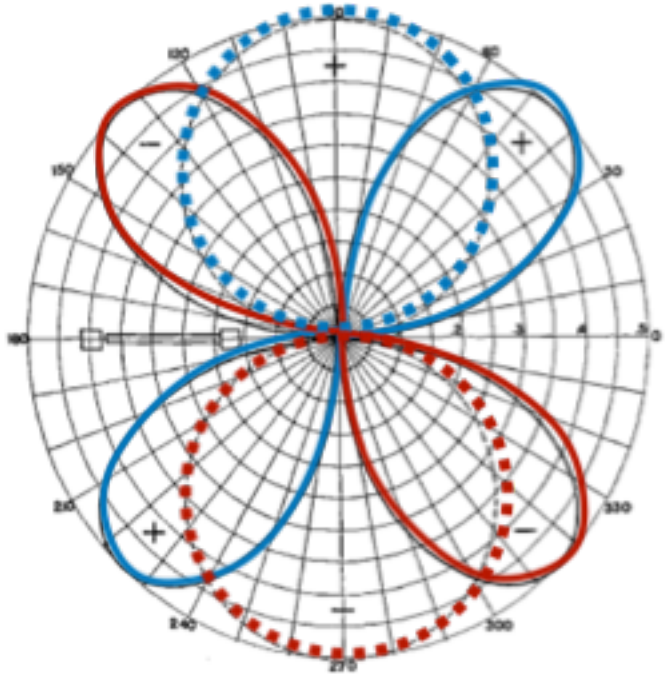
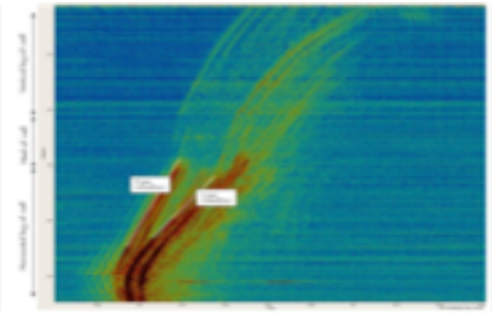


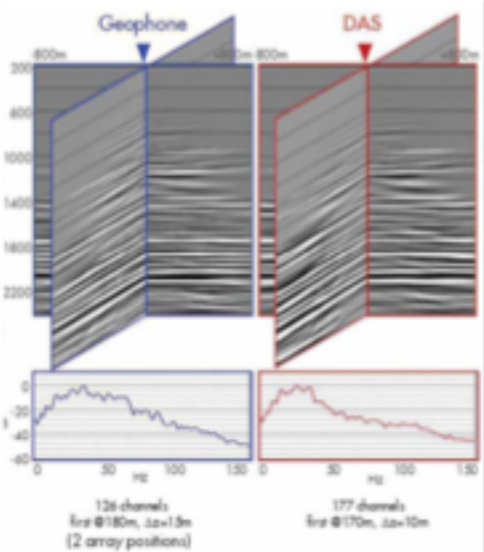
Fig. 8. Directional response characteristic of linear strain seismometer for transverse apparent waves. Pendulum directional response characteristic is shown in dotted lines.

figures from Benioff, BSSA, 1935

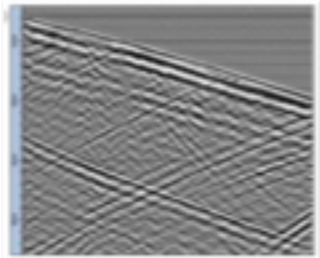
How DAS is used in energy industry

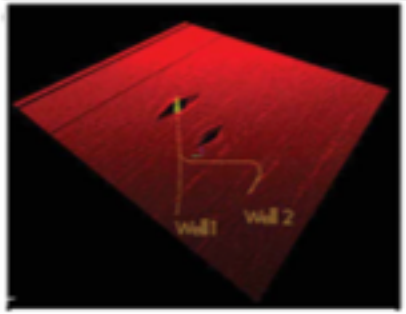


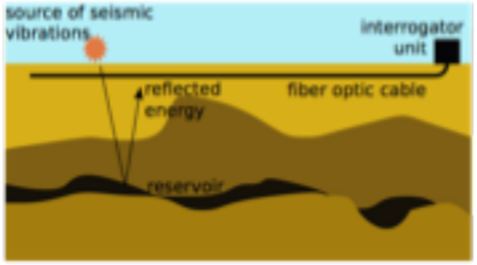
Microseismic monitoring with full well coverage
Webster et al. 2013 SEG Extended Abstracts

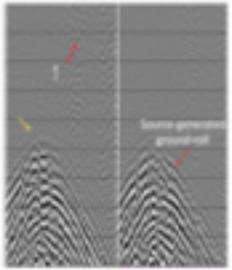


Repeatable 4D seismic offshore and onshore with fiber covering full well
Mateeva et al. 2013 The Leading Edge

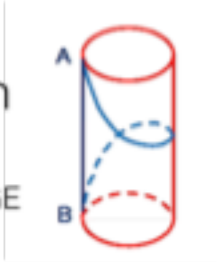








Reflection seismology with helical fibers
Hornman et al. 2013 EAGE Conference Abstracts

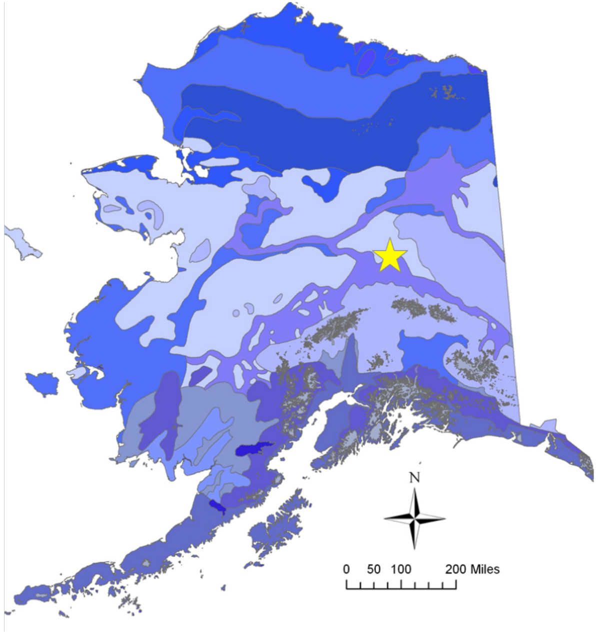


Future applications using existing fiber

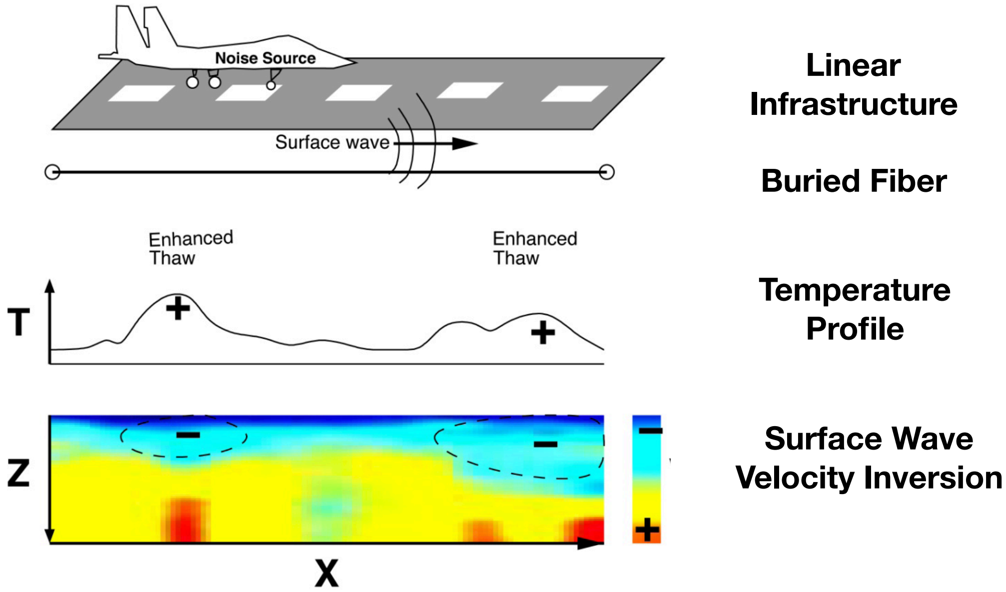
- imaging for earthquake hazard analysis
- permafrost thaw monitoring
- volcano monitoring through seismicity
- early earthquake warning
- induced seismicity location/detection at community scale
- detecting infrastructure problems (broken water mains, sinkholes, potholes, railway misalignment)


NIED

Affordable Permafrost Thaw Monitoring



Map from Alaska Public Lands Information



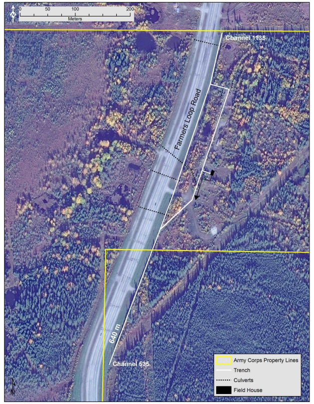
Developing Smart Infrastructure for a Changing Arctic Environment Using Distributed Fiber-Optic Sensing Methods

PI: Jonathan Ajo-Franklin (LBNL), Co-PI: Anna Wagner (CRREL)

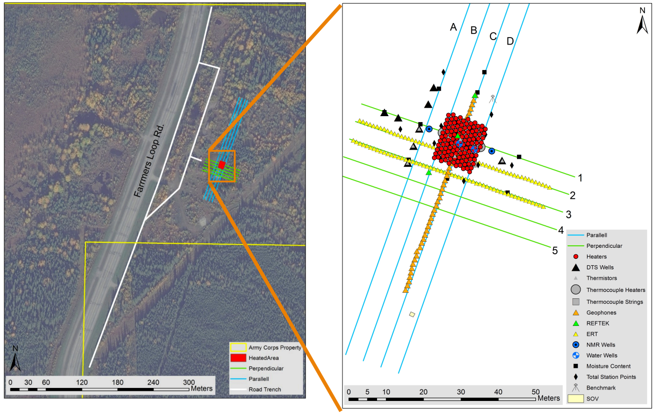
Affordable Permafrost Thaw Monitoring

2014: pilot test
Richmond, CA

2015: linear roadside array
Fairbanks, AK



2016: active thaw, added grid of fiber
Fairbanks, AK

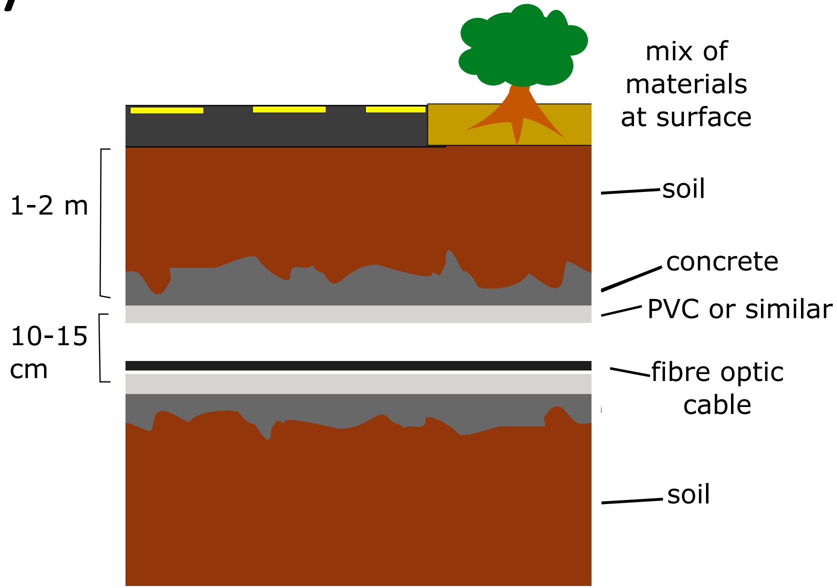


Data collected with iDAS from Silixa

1 meter channel spacing, 10 meter gauge length

1000-2500 samples per second per channel

Earthquake hazard analysis under Stanford



OptaSense ODH-3 interrogator unit
626 channels spanning two loops through figure-eight or
2480 channels spanning a single loop

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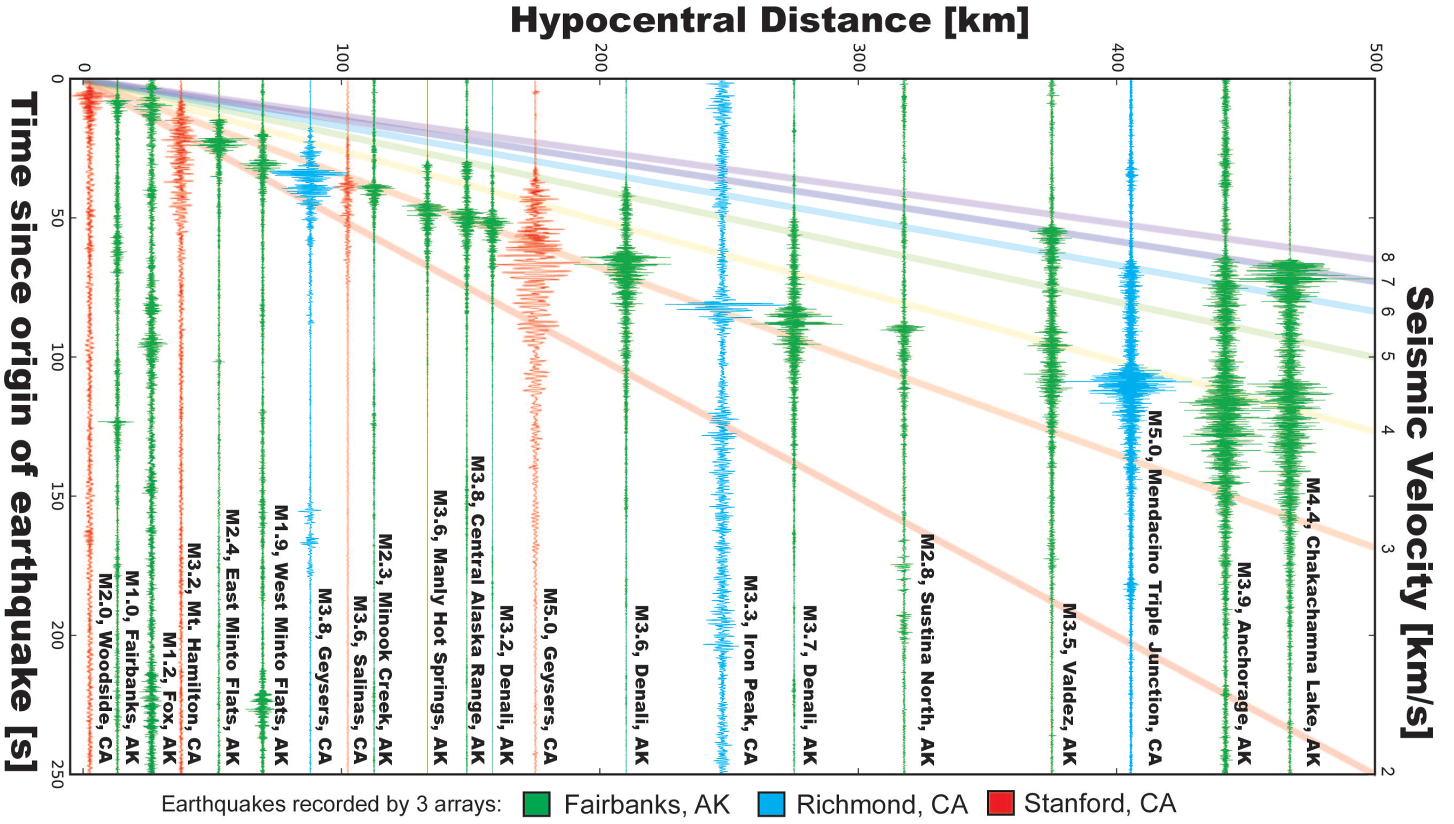
- **We record earthquake arrivals, but different waveforms**
- We can get ambient noise interferometry signals from throughout fiber arrays
- Conclusions and challenges going forwards

Sample events

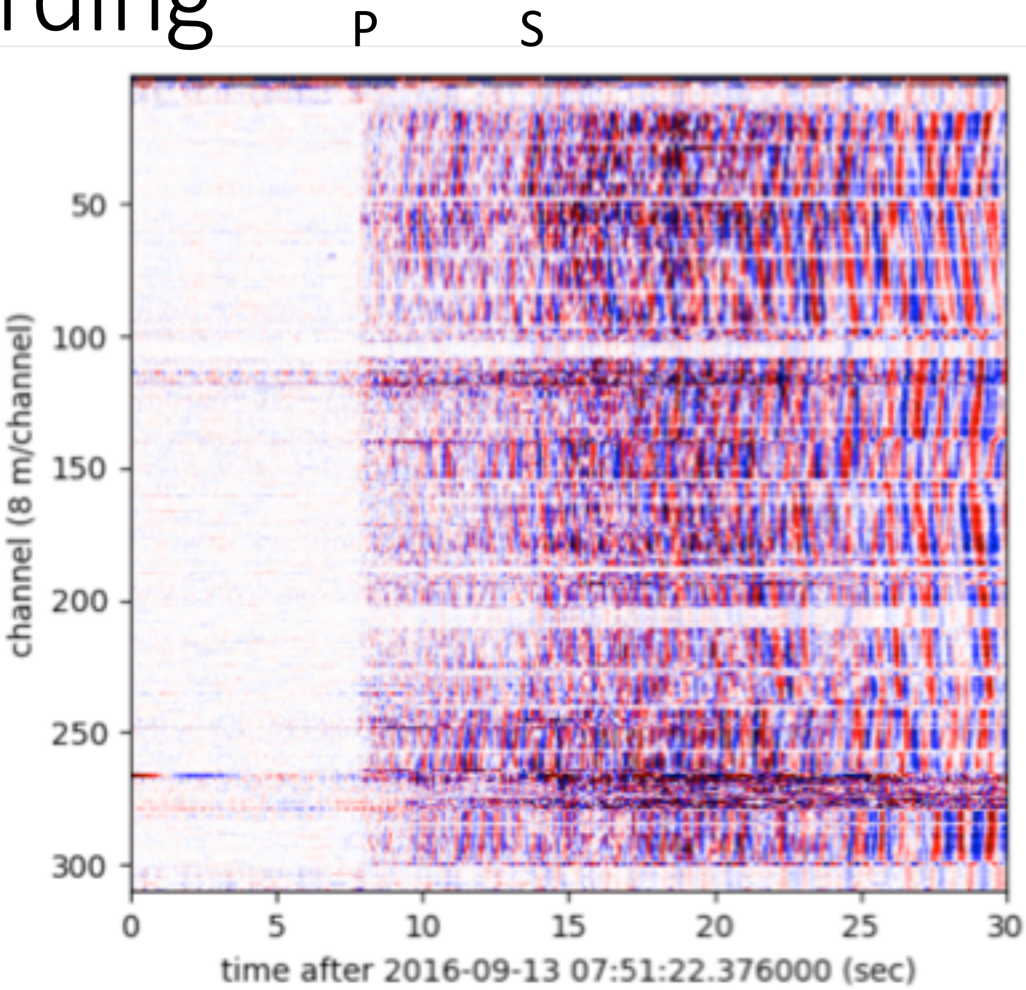


Lindsey et al., GRL, 2017

Raw event data and analysis codes: github.com/eileenrmartin/FiberOpticEarthquakes

A whole-array recording

Magnitude 3.5 earthquake
Sep. 13, 2016
Piedmont, CA

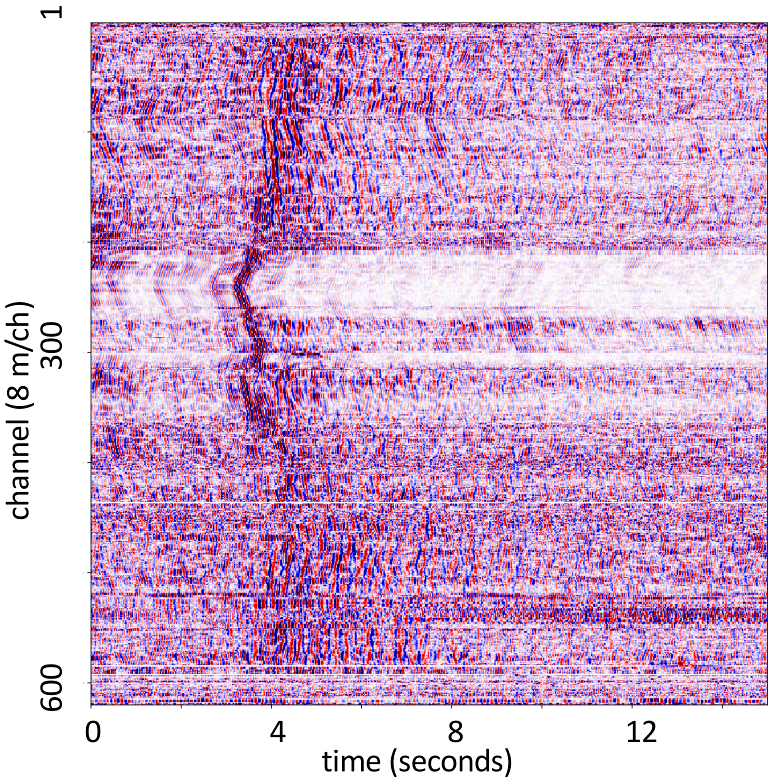


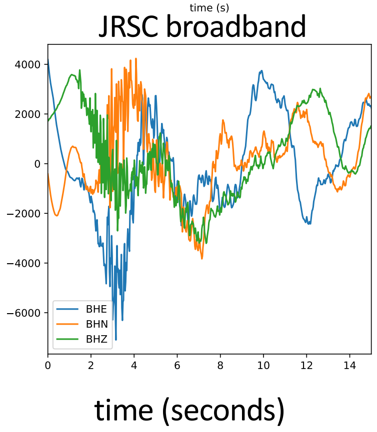
We can detect small, nearby events

figures c/o Siyuan Yuan

event start time UTC: 2017-07-13 04:02:49.08000

distance from array: 5.72 km
magnitude 0.81





Biondi, Martin, Cole, Karrenbach, Lindsey, "Earthquakes analysis using data recorded by the Stanford DAS array," 2017, SEG Ann. Mtg. Expanded Abstracts, 2752-2756.

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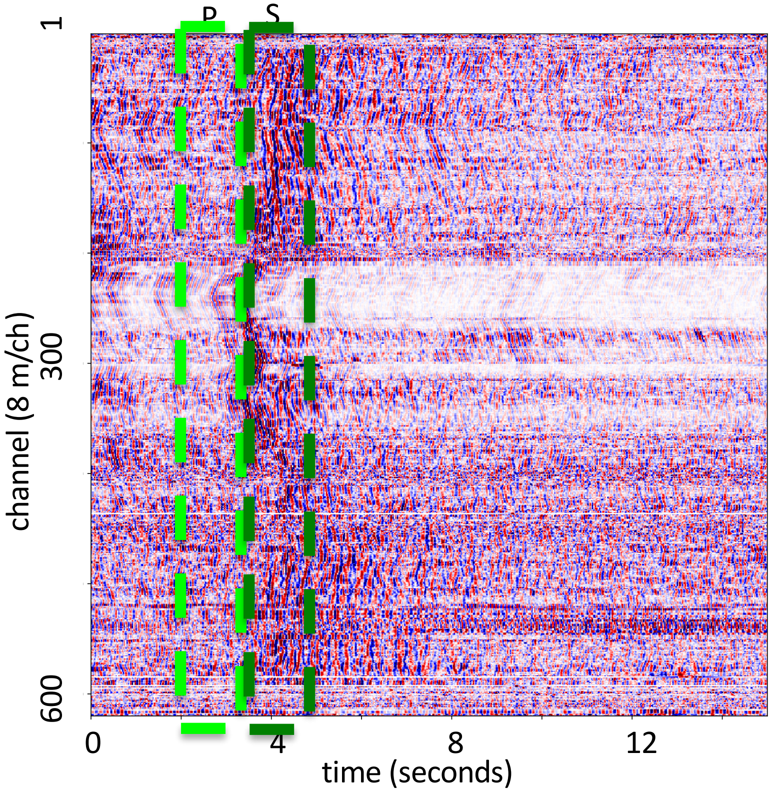

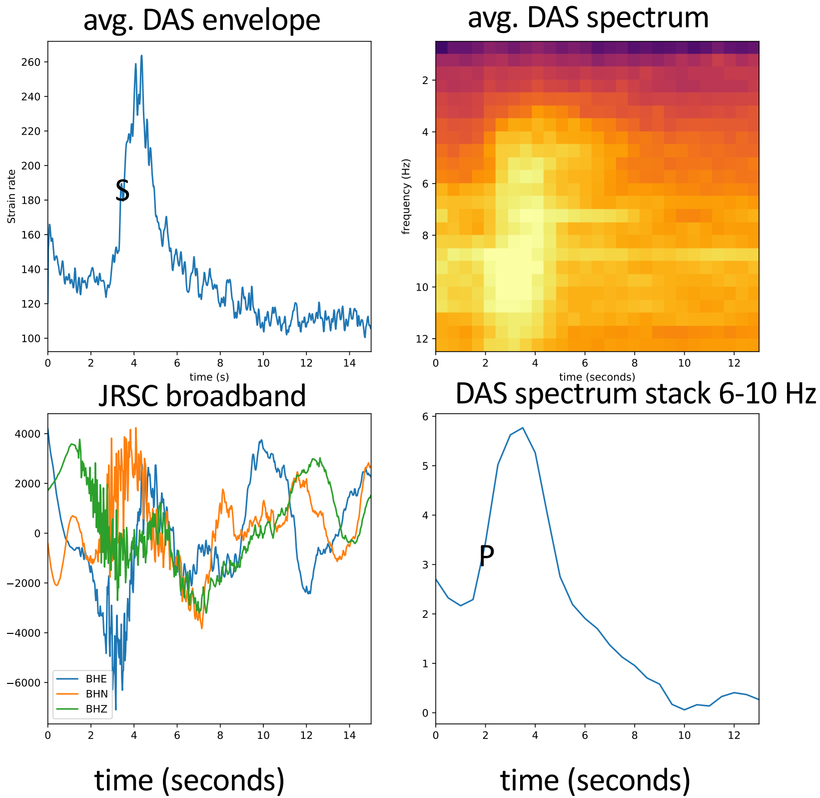

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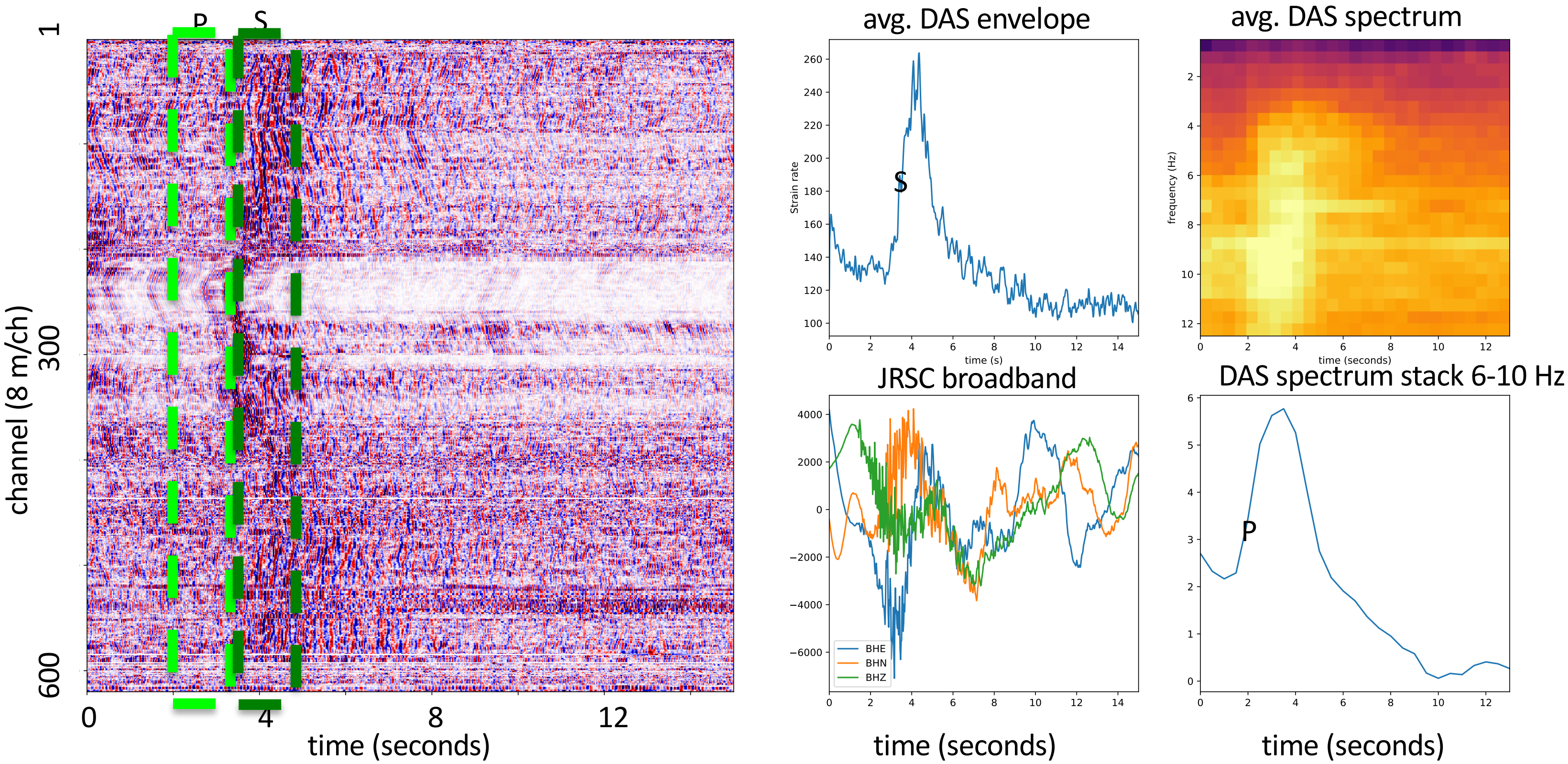

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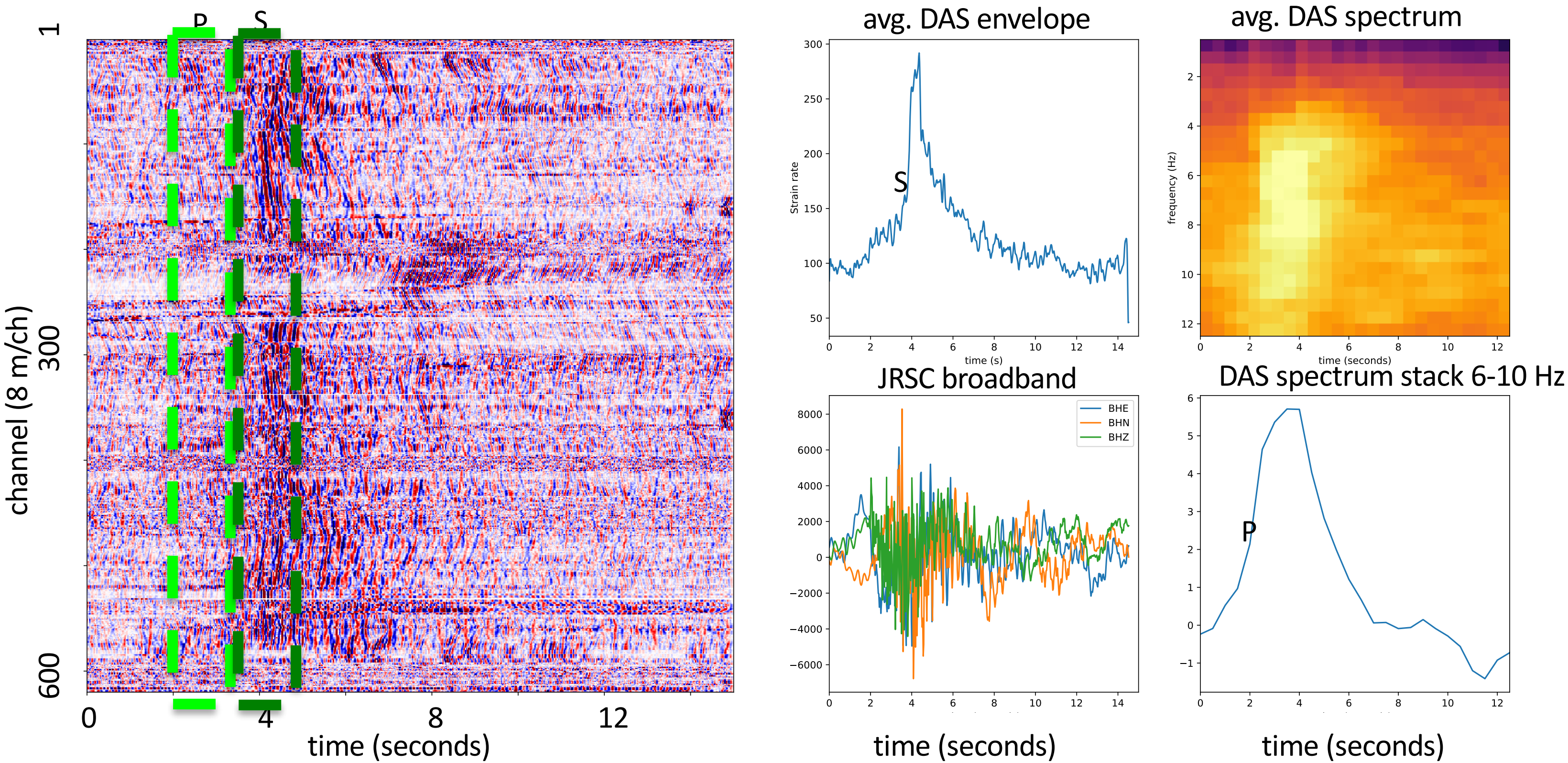
We can detect small, nearby events

figures c/o Siyuan Yuan

event start time UTC: 2017-07-12 18:46:41.67000

distance from array: 5.45 km
magnitude 1.34



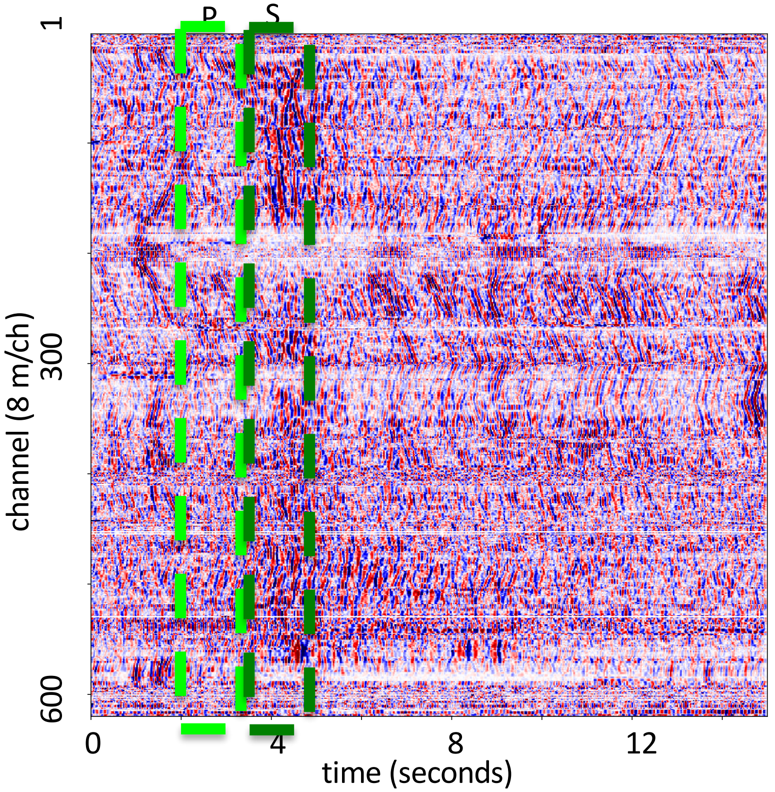
Biondi, Martin, Cole, Karrenbach, Lindsey, “Earthquakes analysis using data recorded by the Stanford DAS array,” 2017, SEG Ann. Mtg. Expanded Abstracts, 2752-2756.

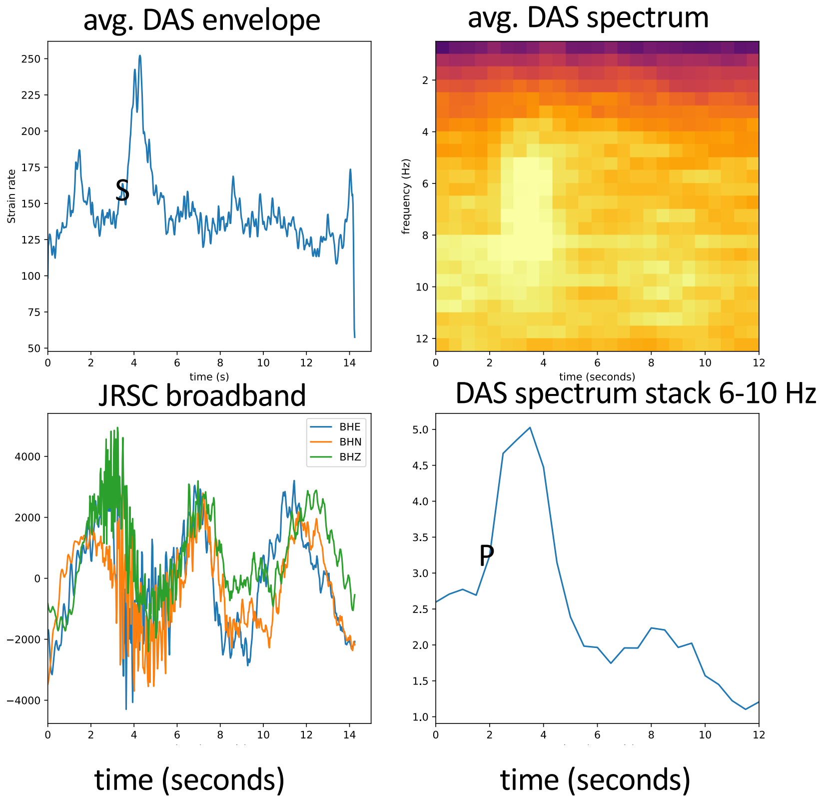
We can detect small, nearby events

figures c/o Siyuan Yuan

event start time UTC: 2017-07-12 18:47:50.63000

distance from array: 5.34 km
magnitude 0.95



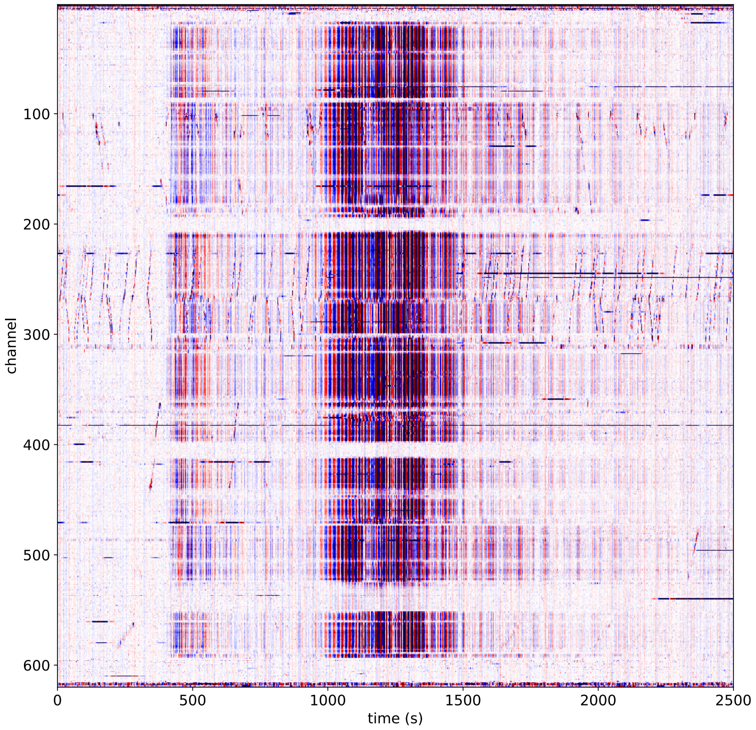


Biondi, Martin, Cole, Karrenbach, Lindsey, “Earthquakes analysis using data recorded by the Stanford DAS array,” 2017, SEG Ann. Mtg. Expanded Abstracts, 2752-2756.

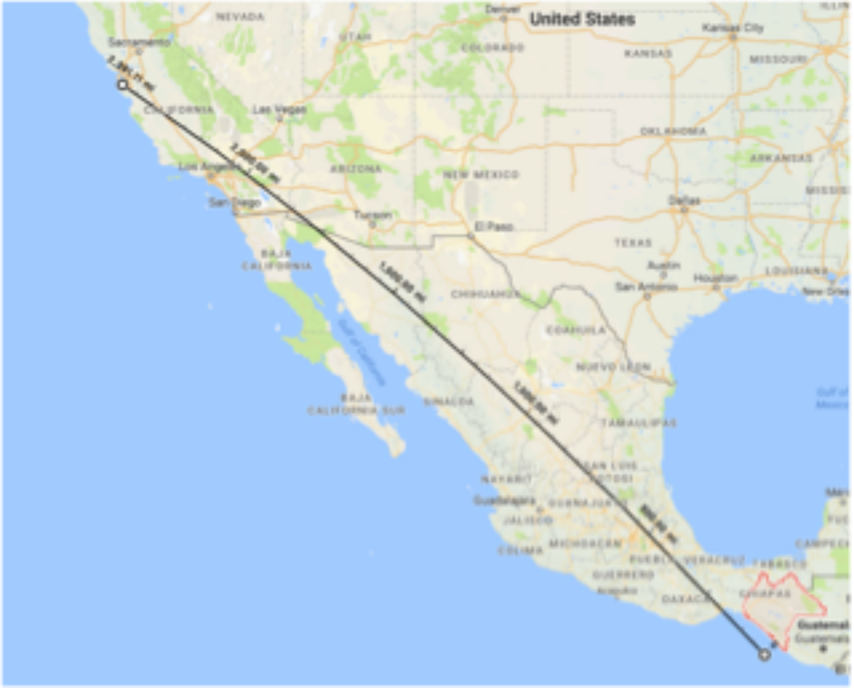
We can also record lower frequencies:

Chiapas, Mexico M8.1

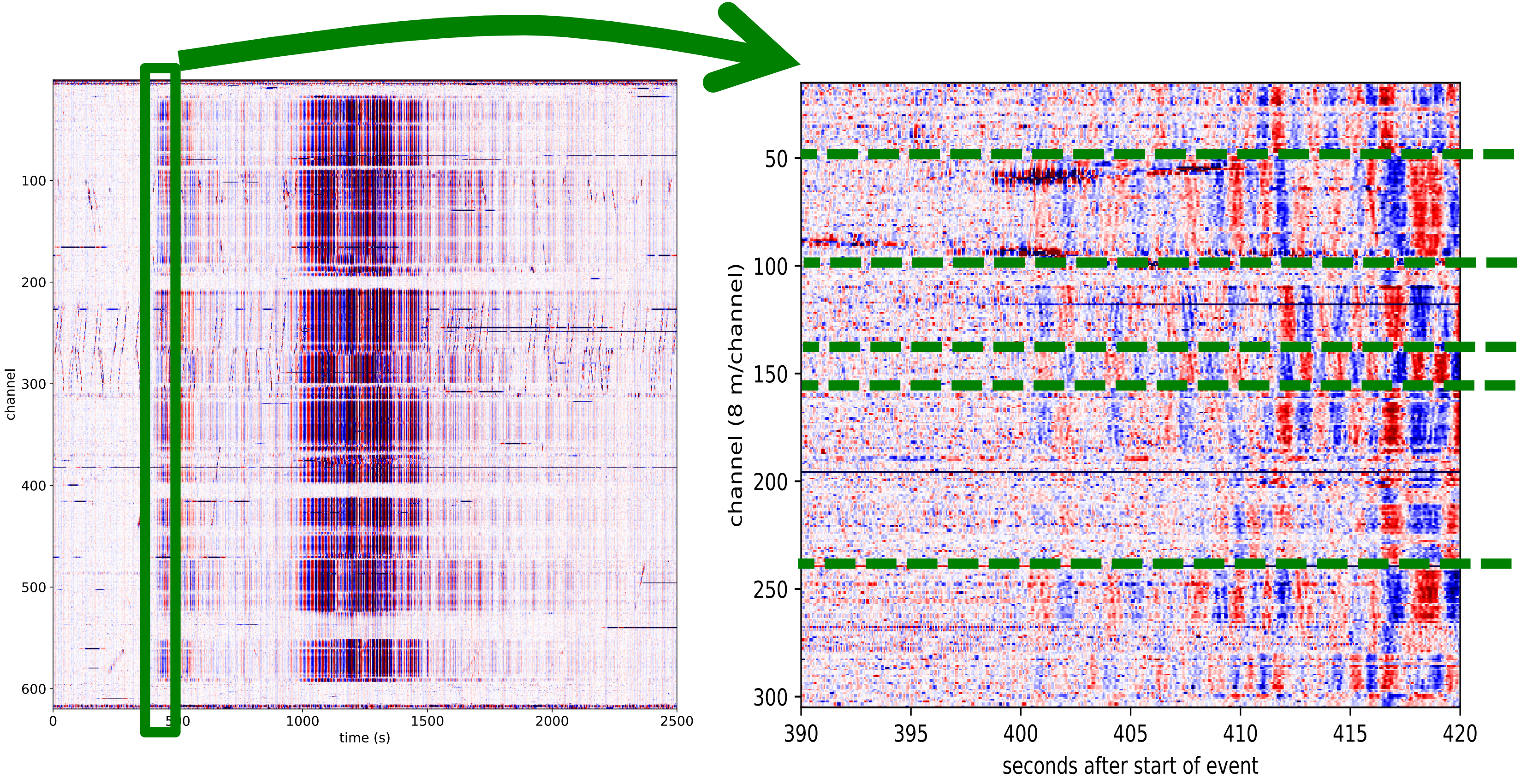
We felt ringing >40 minutes after event



nearly 4000 km away



We mostly record S waves at P arrival



Outline

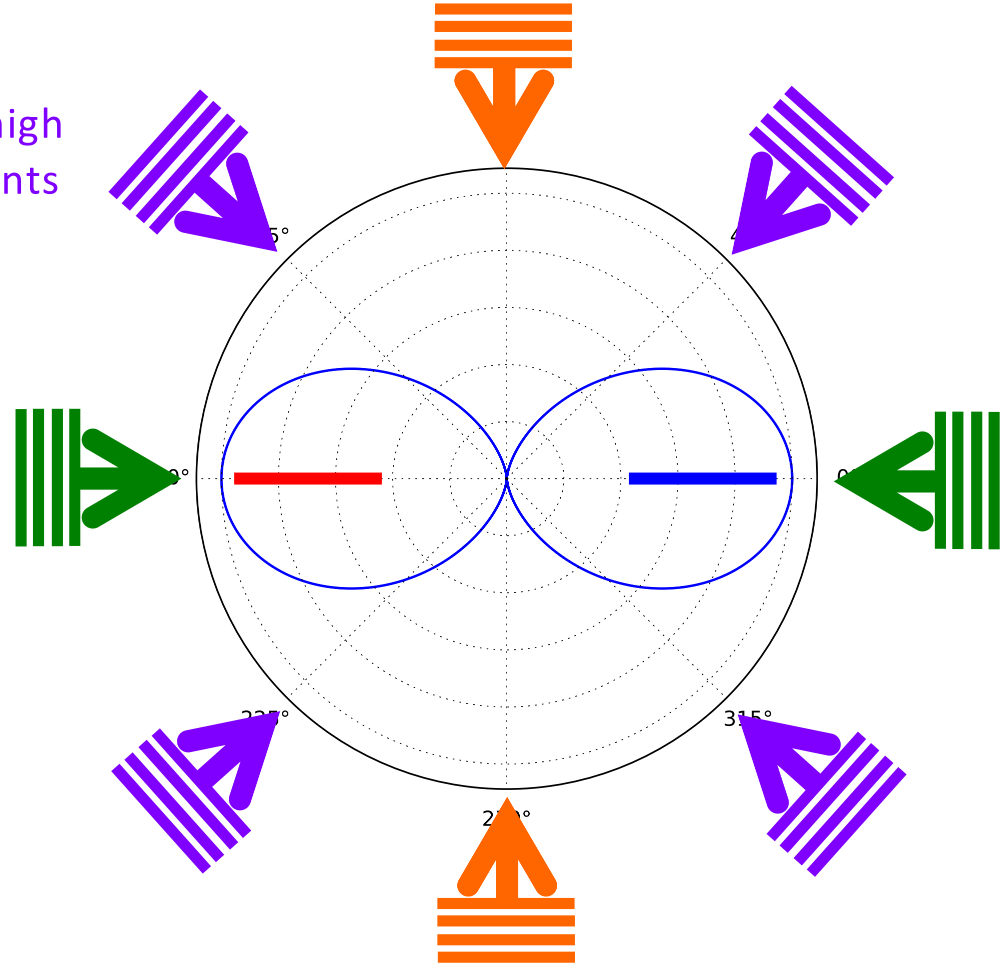
- What is distributed acoustic sensing?
- We record earthquake arrivals, but different waveforms
- **We can get ambient noise interferometry signals from throughout fiber arrays**
  - straightforward to use in linear arrays
  - we get signals throughout 2D arrays, but mix of Love and Rayleigh waves
- Conclusions and challenges going forwards

Co-linear DAS channel xcorrs yield correct Rayleigh wave velocities

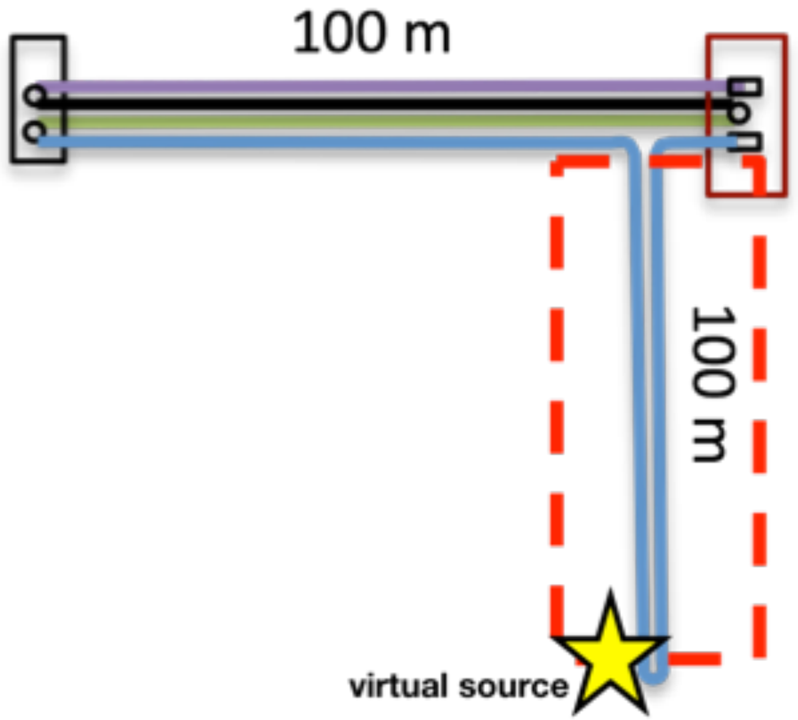
not very sensitive to high apparent velocity events

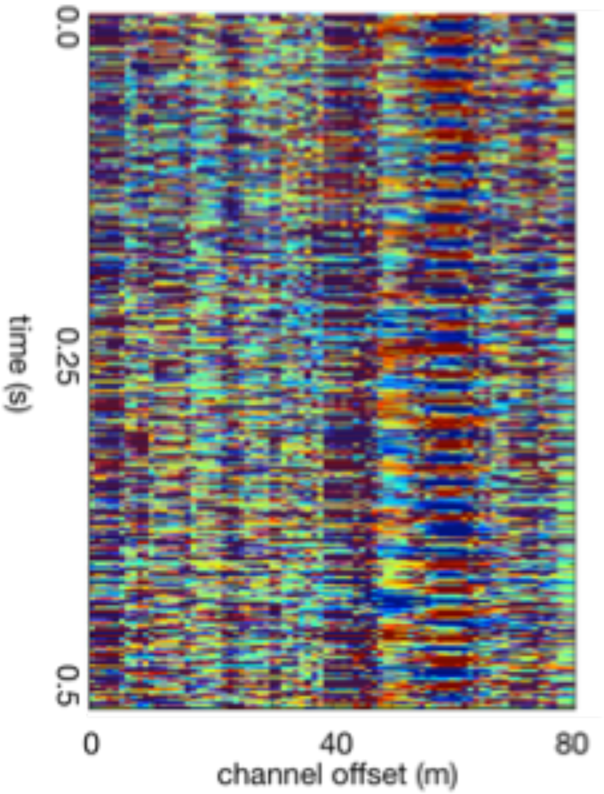
very sensitive to true velocity events

insensitive to infinite velocity events



Richmond Pilot along a line



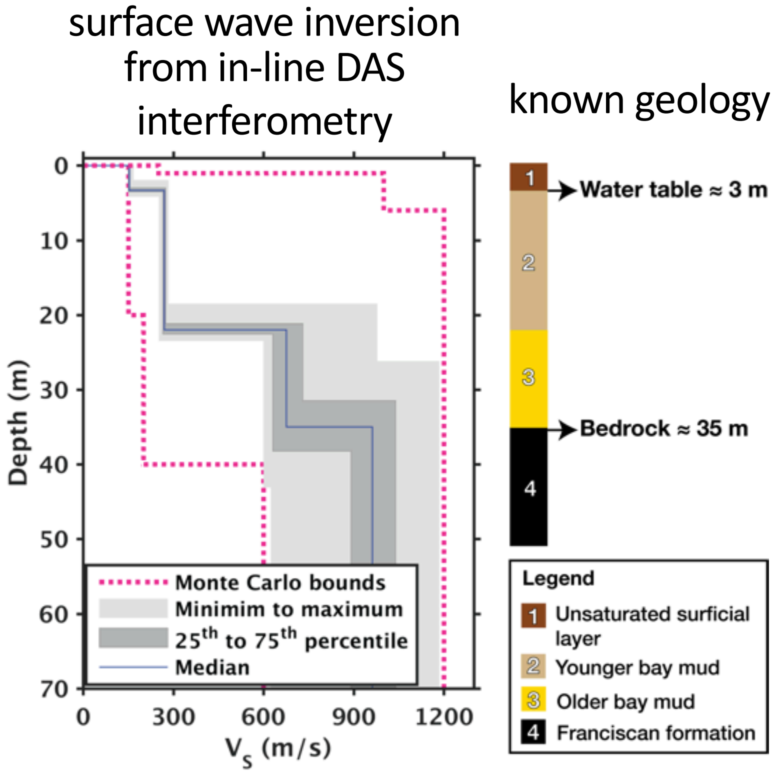


10 minutes yields coherent signals

Virtual source on south end of array ☆
10 minutes of ambient data show coherent signals
Rayleigh wave velocities in 200-400 m/s range

Martin et al., SEG Ann. Mtg. Expanded Abstracts, 2015.

Verified with soil samples from the site

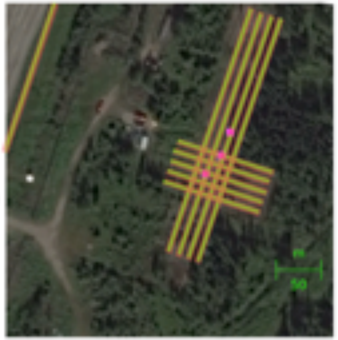


S. Dou et al., Scientific Reports, 2017

We Also Want Signals Between Fiber Lines

Richmond Field Station (LBL, Corps of Engineers)

Fairbanks, AK (LBL, Corps of Engineers)



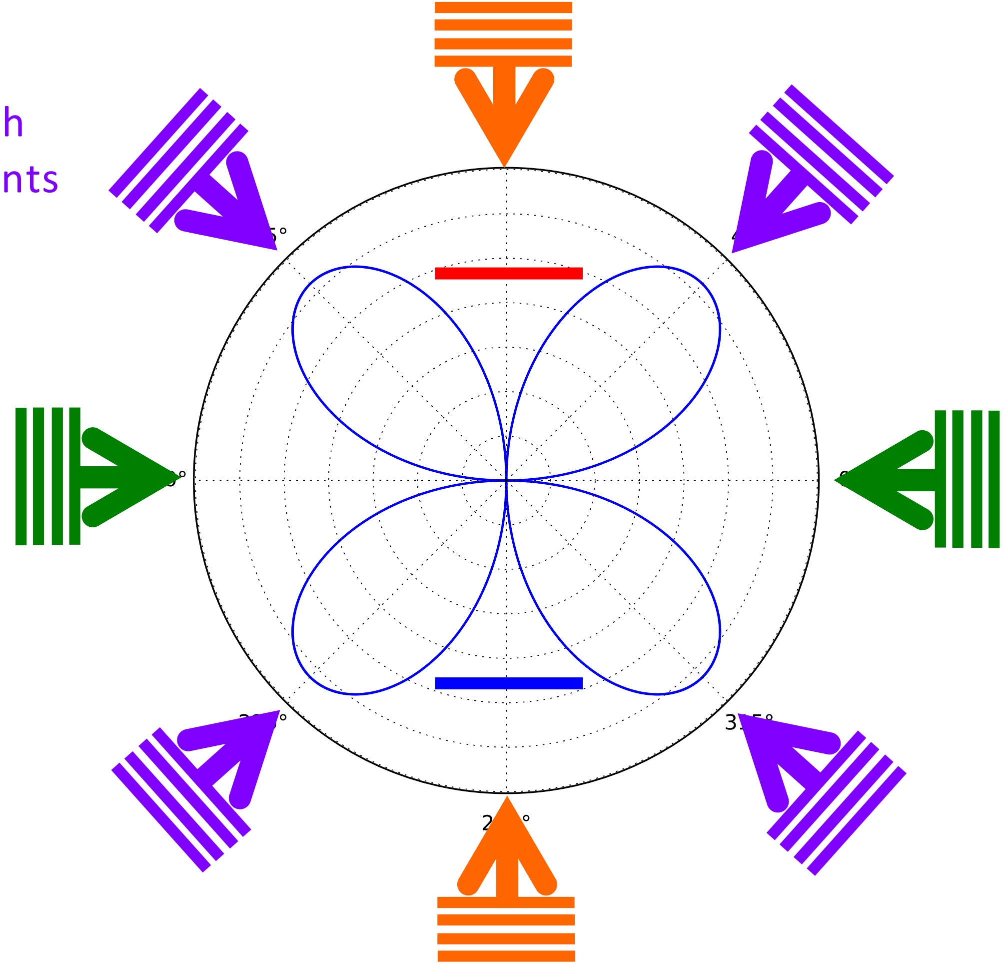
Stanford DAS Array

Transverse DAS xcorrs emphasize the wrong noise sources

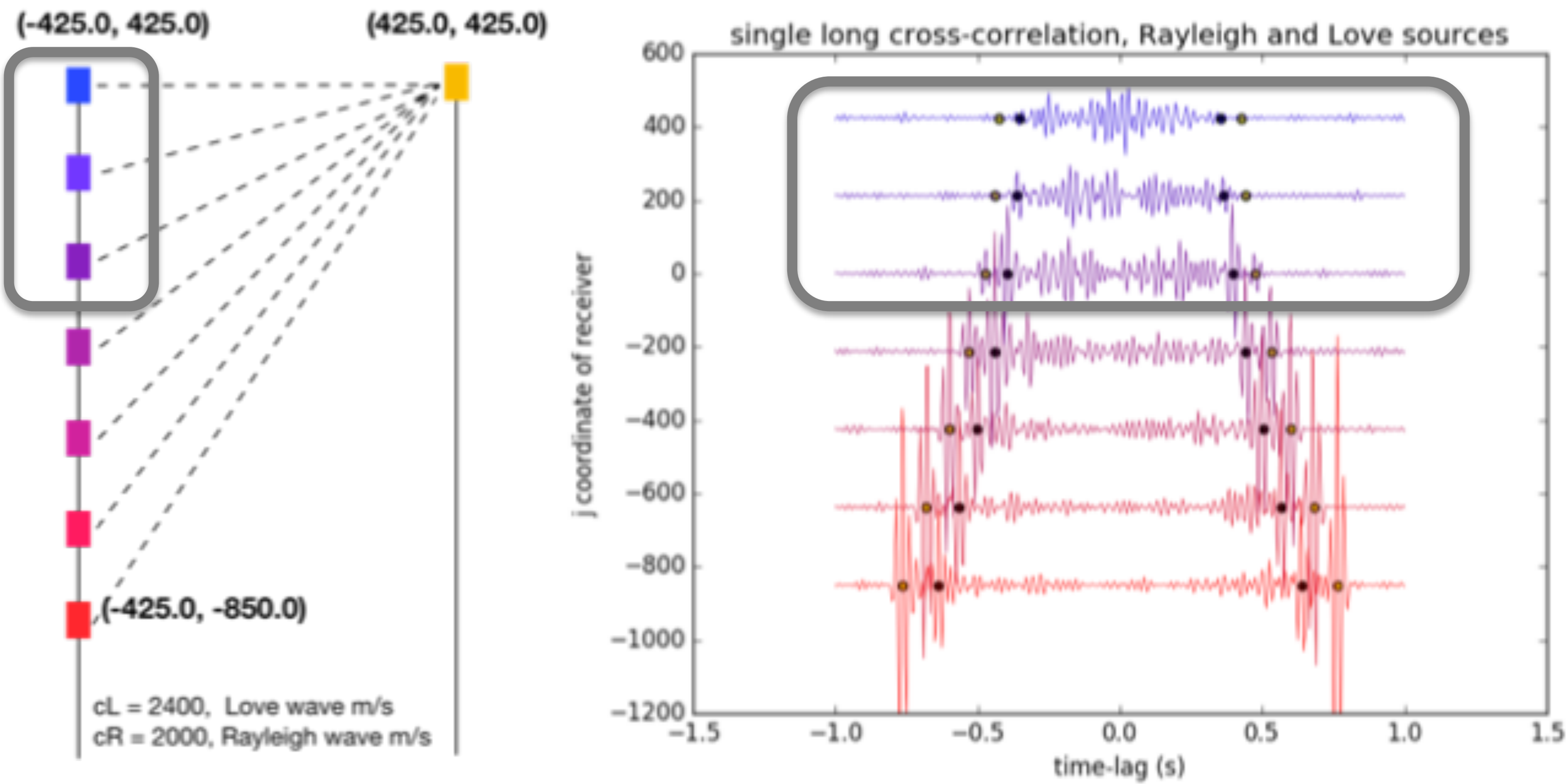
very sensitive to high apparent velocity events

insensitive to infinite apparent velocity events

insensitive to true velocity events

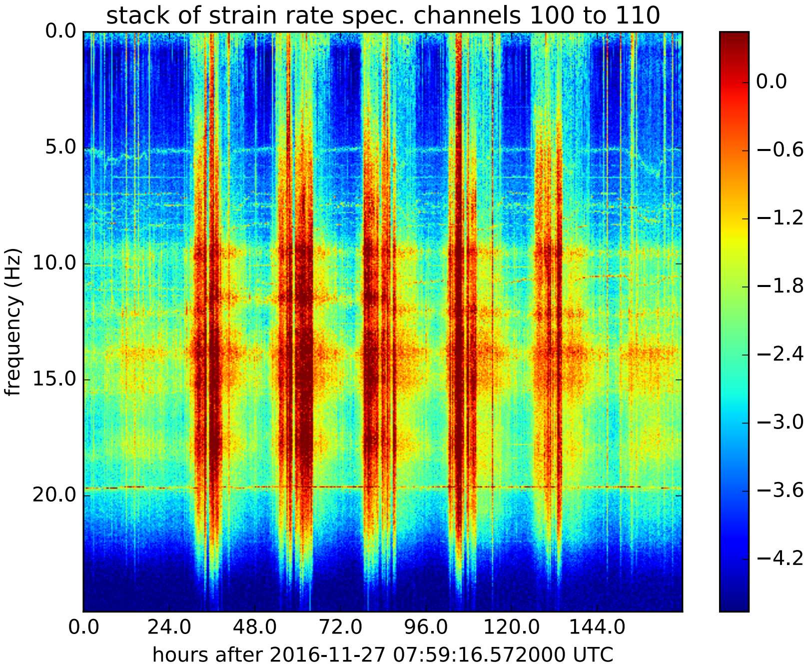


But most parallel channel pairs are useful



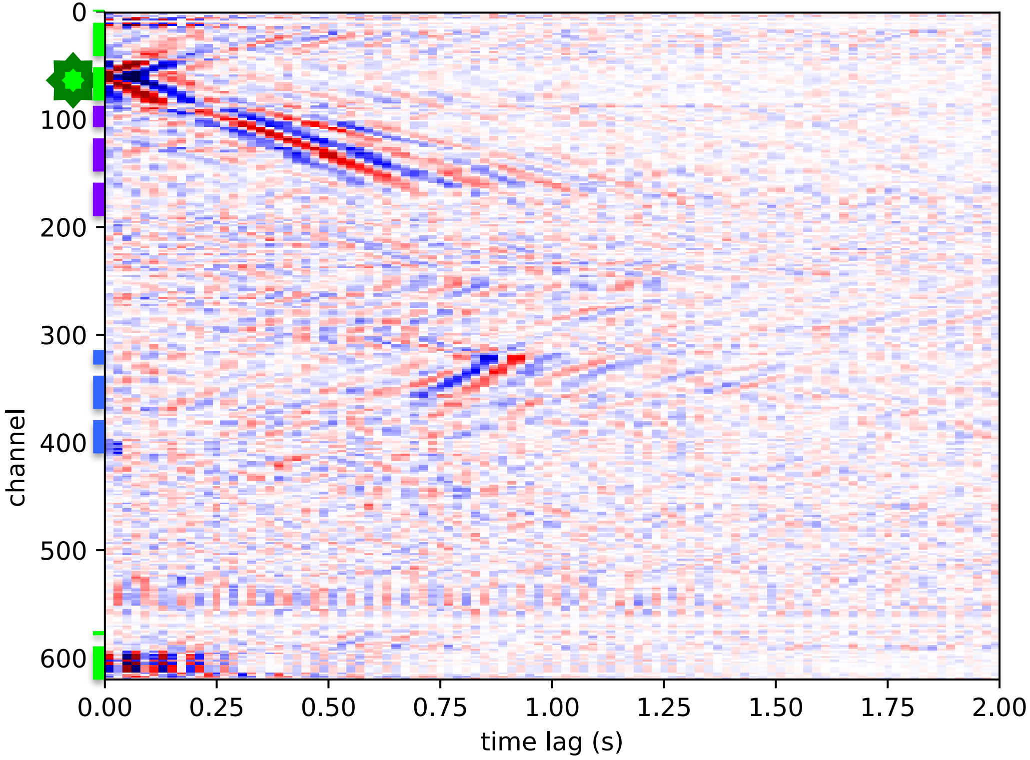
exercise inspire by Wapenaar et al, 2010, Geophysics

Cross-correlations throughout the array in the presence of anthropogenic noise



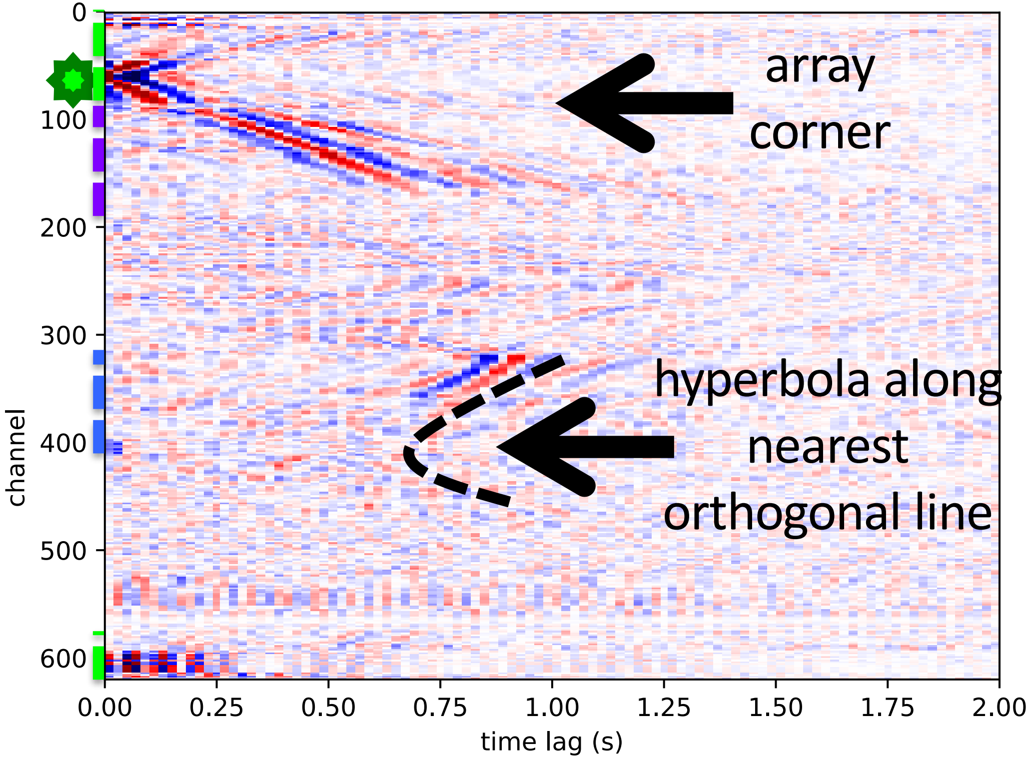
4.08 m effective sensor spacing

We can extract coherent signals throughout the array



Martin et al., IEEE Signal Processing Magazine, 2018.

We can extract coherent signals throughout the array



Martin et al., IEEE Signal Processing Magazine, 2018.

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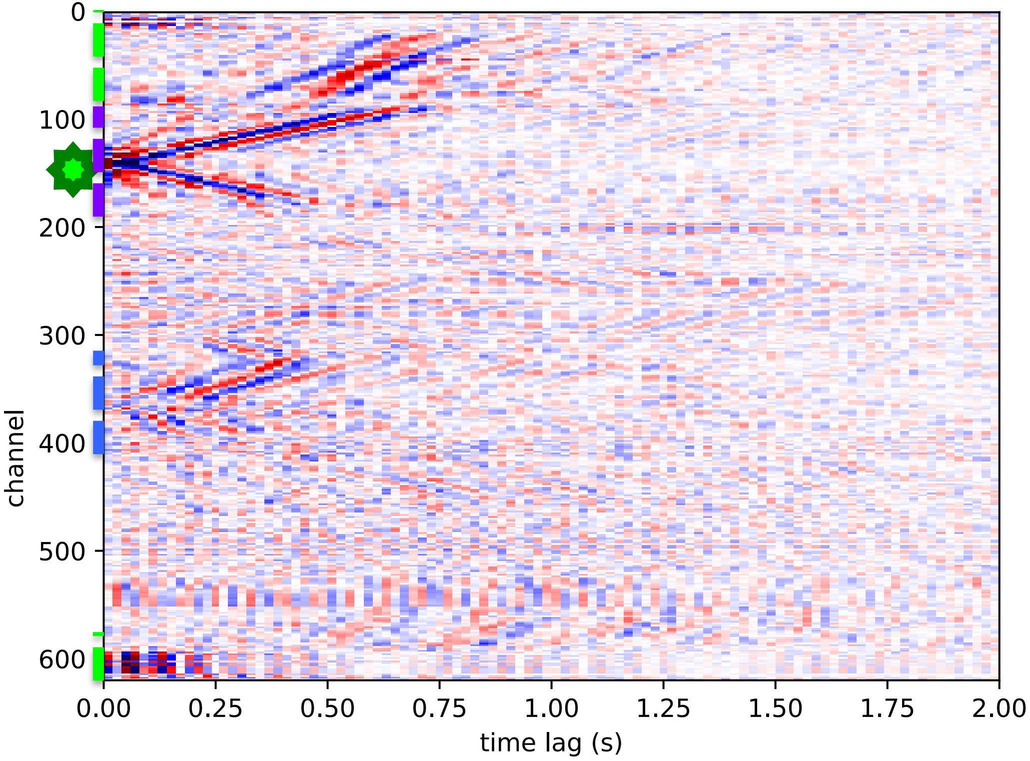

Martin et al., IEEE Signal Processing Magazine, 2018.

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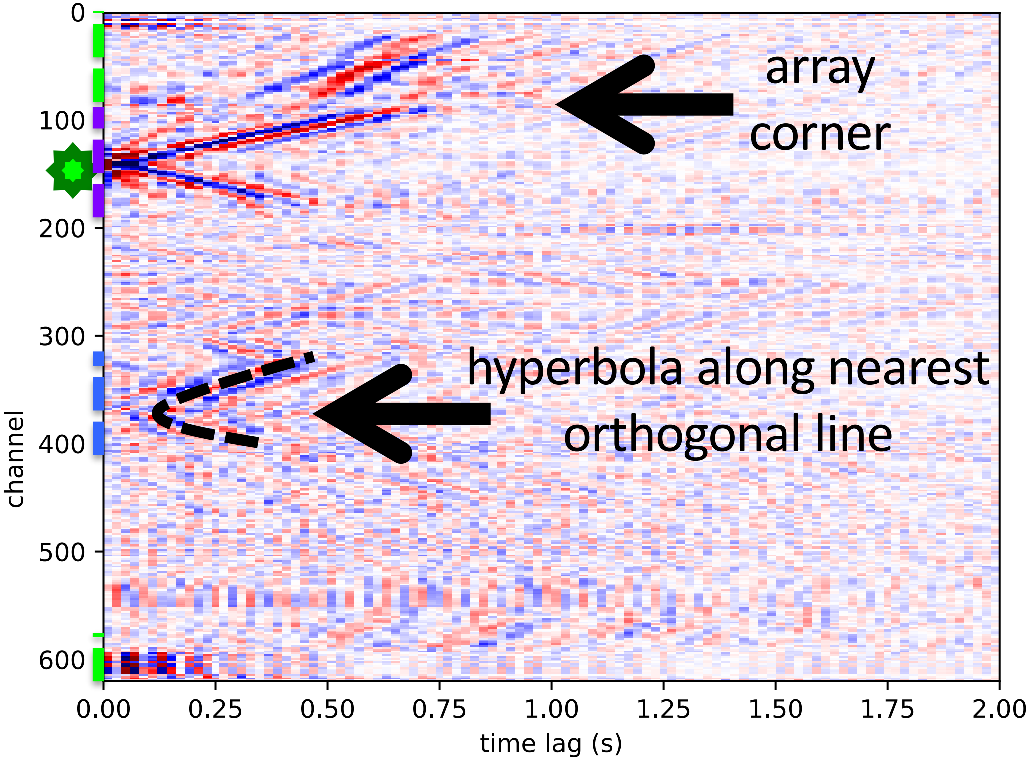
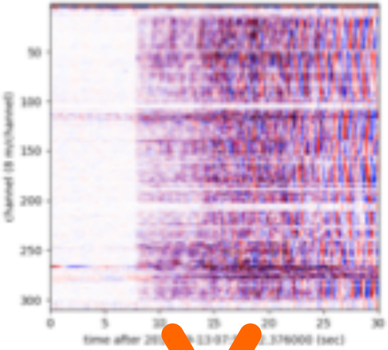


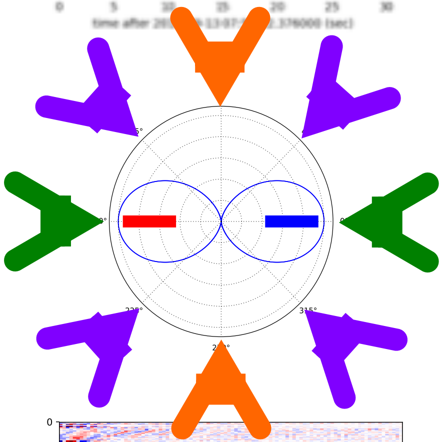
Martin et al., IEEE Signal Processing Magazine, 2018.

Summary

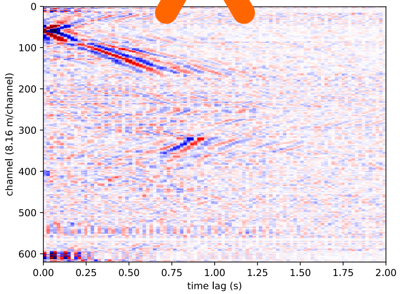
We can obtain dense recordings of earthquakes with reasonable arrival times, but the strain rate waveforms look different.



Ambient noise interferometry with collinear DAS channels is straightforward, verified in theory and in practice.



Ambient noise interferometry yields coherent signals throughout 2D arrays, but only certain sensor pairs are useful, and they can be a mix of Rayleigh and Love waves.



Challenges going forwards

Scalability of algorithms for passive data:
- Many dense sensors
- Streaming data paradigm
- How much data is needed for different applications?

Data in urban areas and around infrastructure:
- Every noise environment is unique, so we need semi-automated noise exploration tools
- Difficult to get exact sensor geometry

Fundamentally different measurements:
- Even methods as simple as beamforming need revamping
- Different sources directions are emphasized

Data Volumes at Stanford

passive

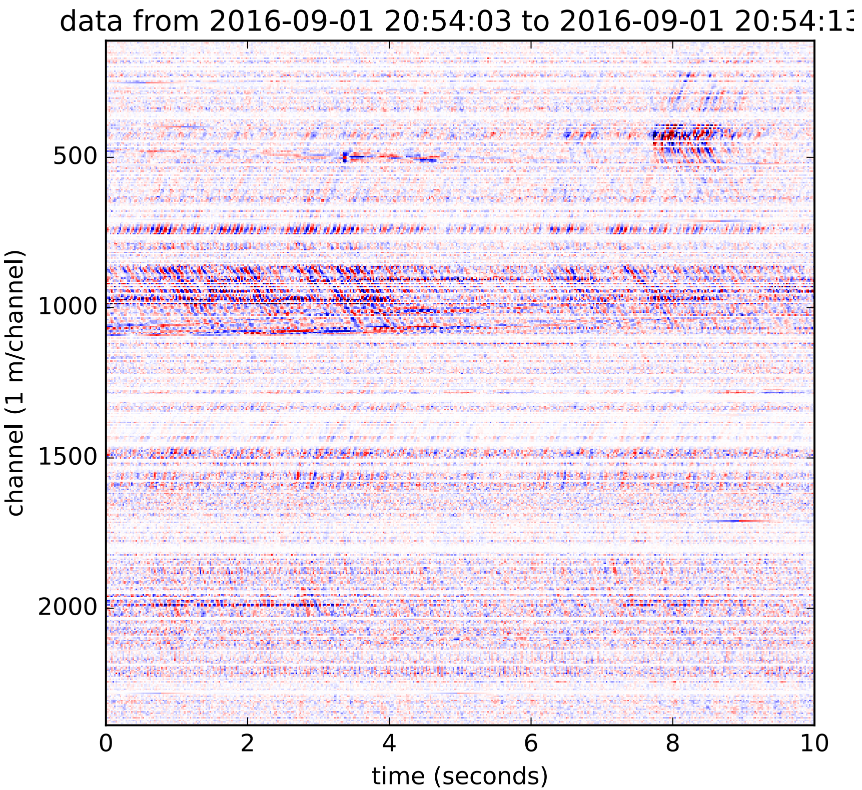
(50 Hz sampling, 8 m spaced double-loop)

active

(2.5 kHz sampling, 1 m spacing)

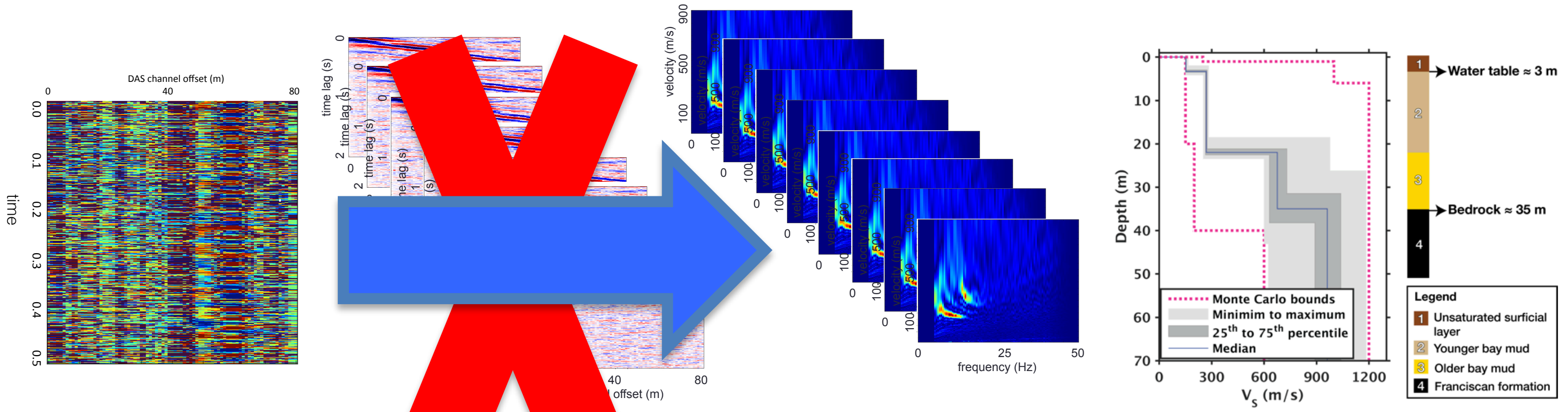
passive
210 days
620 channels
4 bytes/sample
50 samples/second
x 86400 seconds/day
2.04 TB

active
1 day
2480 channels
4 bytes/sample
2500 samples/second
x 86400 seconds/day
1.94 TB



“Big-n” requires fast, streaming algorithms

Example: O(n) dispersion image calculation (or O(n/m) if you have m machines)



raw data
n sensors

n virt urce nse
estimates
via **n² cross-correlations**

n dispersion images with energy at set of (frq,vel) combinations from each virtual source response estimate

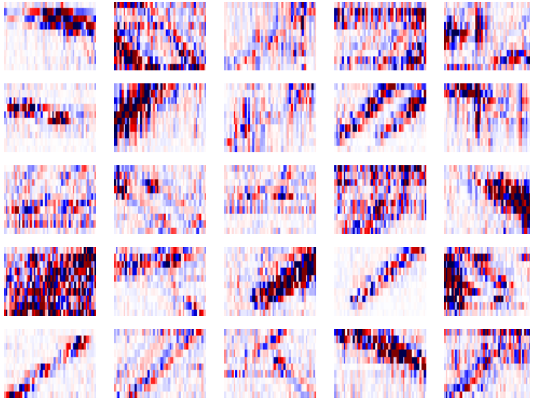
input to dispersion domain surface wave inversion

python serial code available at github.com/eileenrmartin/FastDispersionImages
Algorithm described in dissertation of Martin, 2018

Scaling DAS in urban areas: Machine-learning aided noise characterization

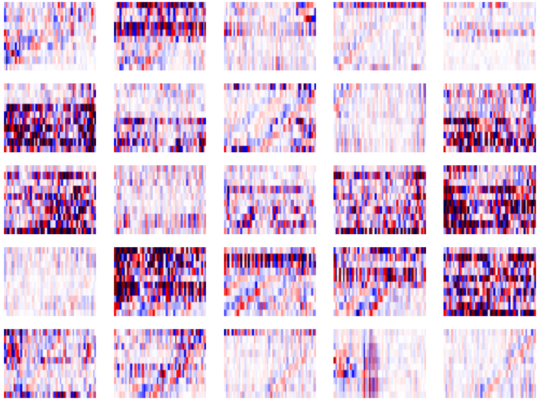
work by Fantine Huot

identified as vehicles



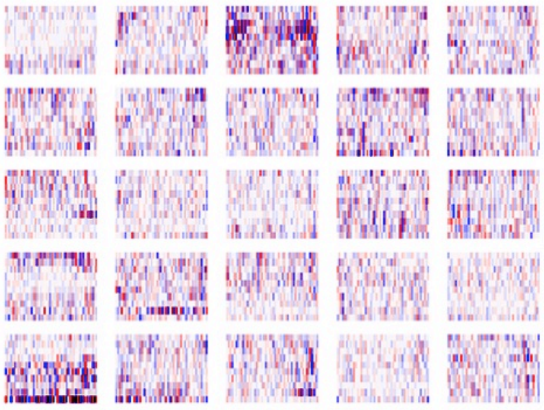
prob(car) > 0.99

borderline cases



0.83 < prob(car) < 0.9

typical ambient noise



Huot, Martin and Biondi, “Automated ambient noise processing,” SEP report 172, 2018.

Huot, Ma, Cieplicki, Martin and Biondi, “Automatic noise exploration in urban areas,” SEG Annual Meeting, 2017.

Martin, Huot, Ma, Cieplicki, Cole, Karrenbach and Biondi “A seismic shift in scalable acquisition demands new processing,” IEEE Signal Proc. Mag. 2018

Acknowledgements

My funding

DOE Computational Science Graduate Fellowship grant DE-FG02-97ER25308

Schlumberger Innovation Fellowship

Affiliates of the Stanford Exploration Project

Stanford Fiber Optic Seismic Observatory

PI: Biondo Biondi

OptaSense provided interrogator unit, and support of Dr. Steve Cole and Dr. Martin Karrenbach

Stanford IT, School of Earth Sciences IT, and Stanford Center for Computational Earth and Environmental Sciences (particularly Dr. Bob Clapp)

Chris Castillo for field work assistance

Developing Smart Infrastructure for a Changing Arctic Environment Using Distributed Fiber-optic Sensing Methods

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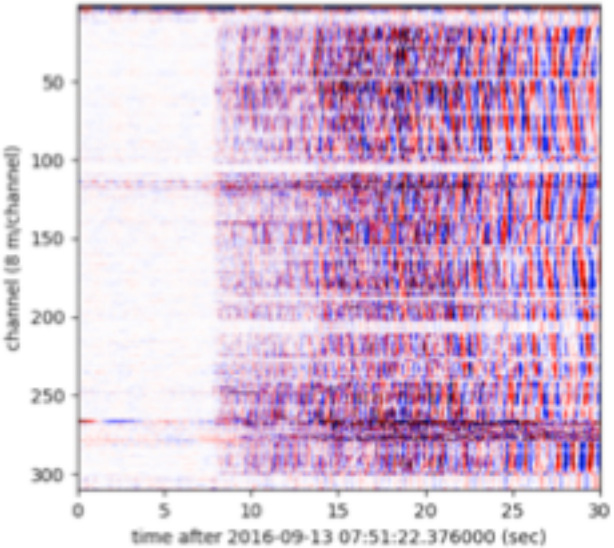
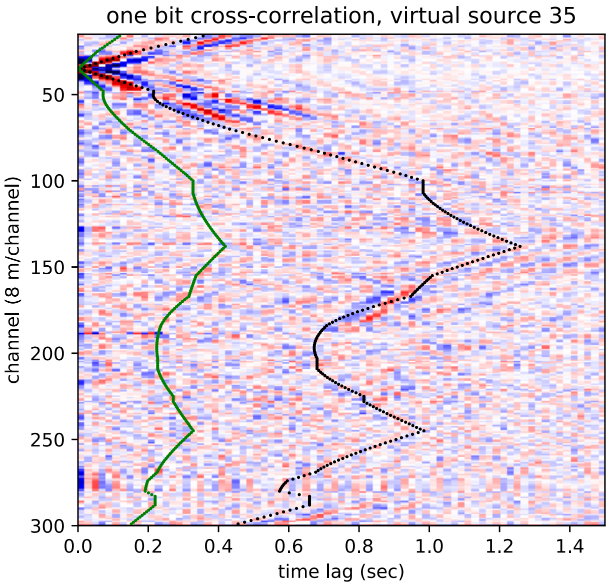
Collaborators: Nate Lindsey (Cal/LBL), Shan Dou (LBL), Tom Daley (LBL), Barry Freifeld (LBL), Michelle Robertson (LBL), Craig Ulrich (LBL), Stephanie James (USGS, formerly UF), Kevin Bjella (CRREL), Ian Ekblaw (LBL)

SERDP grant RC-2437

Questions?





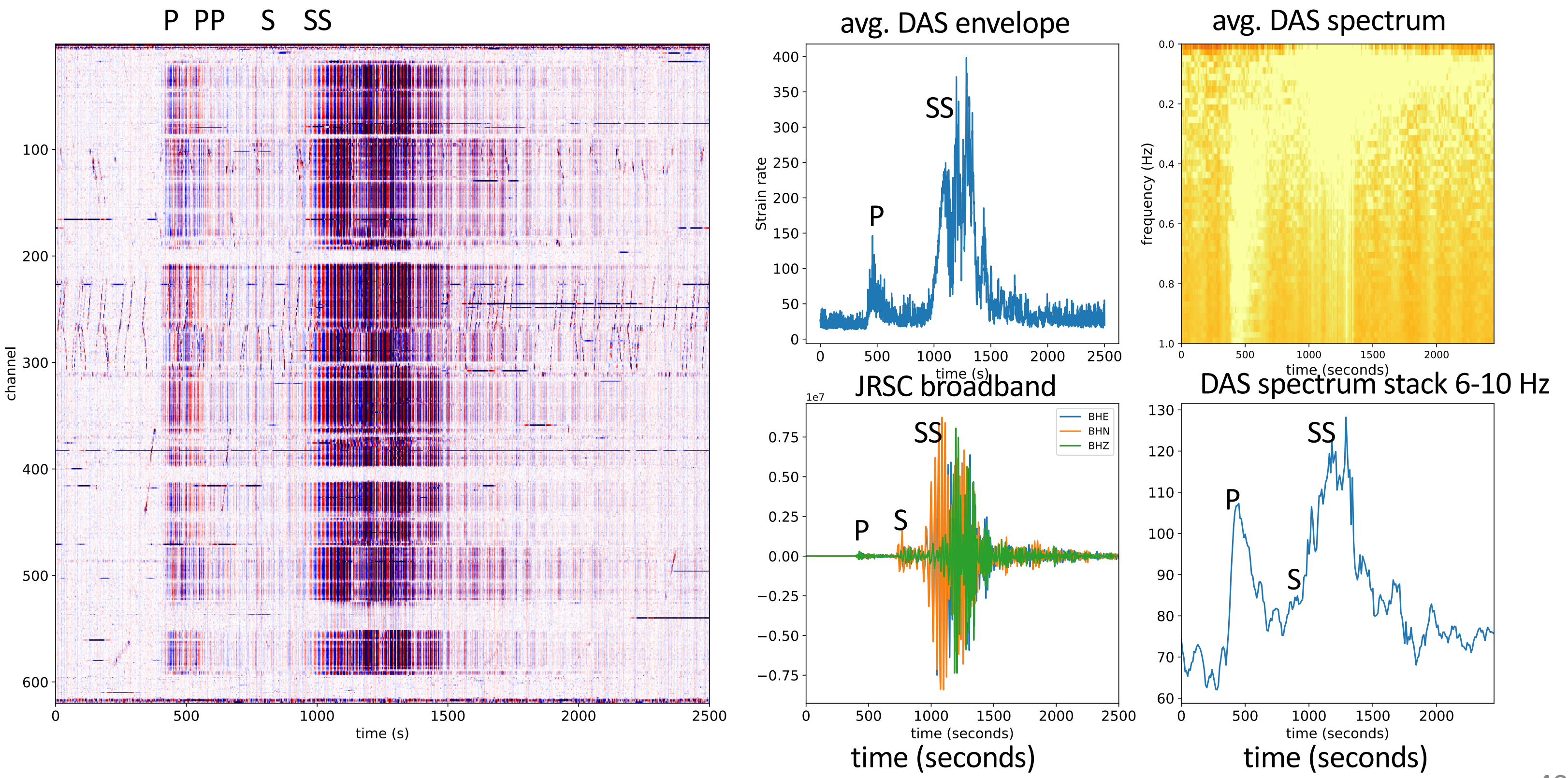
Website: eileenrmartin.github.io

EQ data and plots: github.com/eileenrmartin/FiberOpticEarthquakes

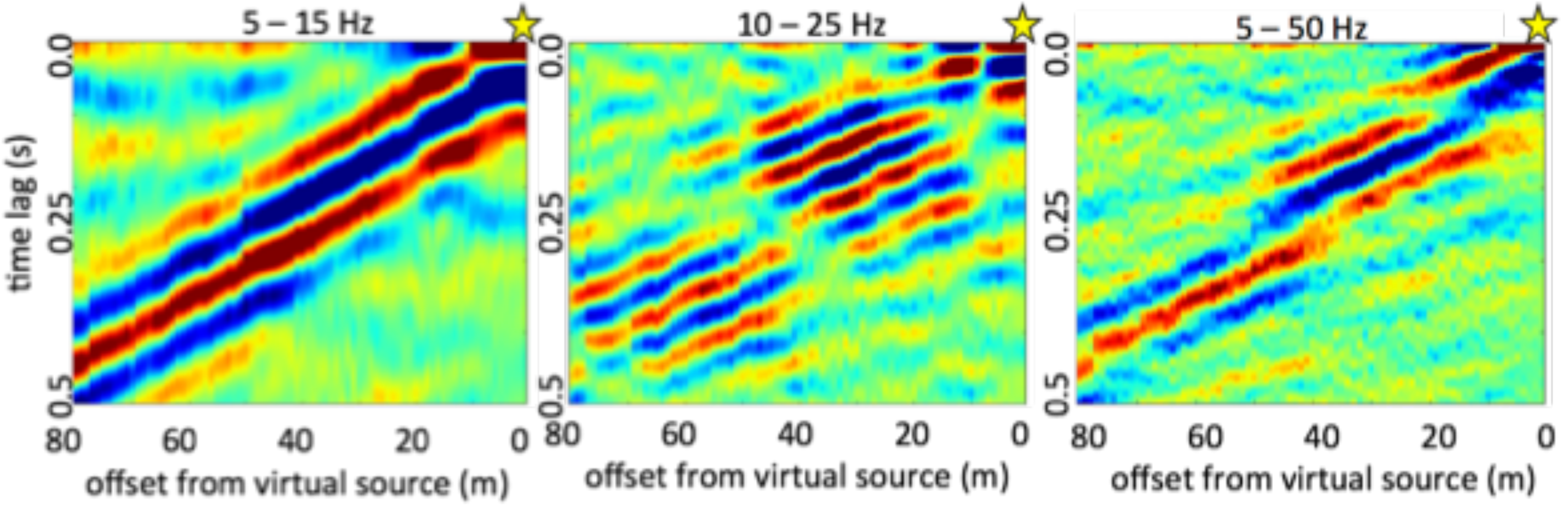
Fast dispersion image code: github.com/eileenrmartin/FastDispersionImages
(or email me for C++ multithreaded code)

Comparison to JRSC broadband

figure c/o
Siyuan Yuan



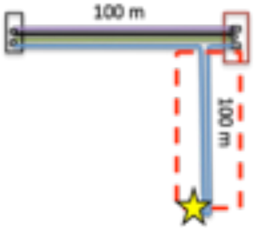
10 minutes yields coherent signals



Virtual source on south end of array ☆

10 minutes of ambient data show coherent signals

Rayleigh wave velocities in 200-400 m/s range



Martin et al., SEG Ann. Mtg. Expanded Abstracts, 2015.